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EVALUATION OF ARMCO PH13-8Mo

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Renton, Washington

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THE BOEING COMPANY

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ABSTRACT

The PH 13-8 Mo is a precipitation hardenable stainless steel developed by the Armco Steel Corporation. This steel can be heat treated to 225 ksi and has excellent toughness, general corrosion, and stress corrosion at this strength level. The fatigue life is comparable to 4330 in both the smooth and notched conditions.

Exposure to temperatures in the 800° to 900°F range for extended times reduces the toughness of this steel and use in this temperature range is not recommended.

KEY WORDS

Stainless Steel
Maraging
Tensile
Stress Corrosion
Precipitation Hardening
Fracture Toughness
Fatigue

1.0 INTRODUCTION

Recent developments in stainless steel technology has resulted in several high strength stainless steel alloys which have attractive properties for structural applications. These steels are high in chromium and exhibit stainless qualities. The alloys which were selected for evaluation were Armco's PH 13-8Mo, and Carpenter's Custom 455 and Pyromet X-15. Since these alloys have similar properties, the reports for each alloy will be published as separate documents to avoid confusion. This report will cover the test work on Armco PH 13-8Mo.

Armco has been a pioneer in the development of precipitation hardening grades of stainless steels, i.e., 17-7Ph, PH15-7Mo, 17-4Ph, and others. The latest of their precipitation hardening steels is PH13-8Mo which has shown good strength, toughness, and stress corrosion resistance.

2.0 MATERIAL

The test material used for this investigation was obtained from the Baltimore Division of the Armco Steel Company. The 4" RCS x 34" long billet was made from a double vacuum melted ingot. This billet was received in the hot rolled and ground conditions. The certified chemical composition is shown below together with the nominal composition range:

Element	Nominal Composition (Wt.%)	Ht-2V-0037 Certified Composition (Wt.%)
Cr	12.25-13.25	13.03
Ni	7.50- 8.50	8.30
Mo	2.00- 2.50	2.14
Al	0.90- 1.35	1.06
C	0.05 Max	.032
Mn	0.10 Max	.01
P	0.010 Max	.002
S	0.008 Max	.005
Si	0.10 Max	.03
N	0.01 Max	Not Reported
Fe	Balance	Balance

A 3/8" thick cross section was taken from the center of the billet for macro inspection. It was ground, polished, and etched with a macro solution of 4 parts HCL, 4 parts H_2O, and 1 part HNO_3 at 160°F. The structure was very uniform in appearance with no indications of segregation, banding, or delaminations. The photo macrograph is presented in Figure 1.

The metallurgical structure of PH13-8Mo is a carbon-free martensite that is hardened by precipitation hardening. This martensite is soft in the solution treated (annealed) condition and depends on the precipitation of intermetallic compounds for strengthening. This strengthening mechanism is similar to that of 18% nickel maraging steels. However, unlike the 18% nickel steel which will rust, the PH13-8Mo maraging steel is stainless and is quite resistant to atmospheric corrosion.

The PH13-8Mo is commercially produced as a double vacuum melted steel (VIM + VAR) and is available as plate, bar, and forging stock at a base price of $3.00 per pound.

3.0 HEAT TREATMENT

The composition of the PH13-8Mo requires a solution temperature of 1700°F to insure that all phases are in solid solution with the matrix. Upon rapid cooling from this temperature, the martensitic transformation starts at about 250°F and finishes at about 70°F. In this condition, the material is soft and can be readily machined. The second phase of heat treatment is the aging or precipitation cycle. The solution treated material can be aged at temperatures ranging from 950°F to 1100°F, depending on the strength level required. The lower aging temperatures will give the highest strengths. The heat treatment recommended by the vendor to achieve maximum strength is to solution for 1 hour at 1700°F and oil quench to 60°F; this is to be followed by 4 hours at 950°F for the aging cycle.

The effects of solution and aging temperatures were investigated to confirm the vendor's data and to determine the temperature limits which could be tolerated. Solution temperatures at 1600°F, 1700°F, and 1800°F were investigated and the effects on the microstructures are presented in Figure 2. Aging temperatures from 700°F to 1700°F were used to study the effects of temperature on hardness and microstructure, and the results are presented in Figures 3 and 4.

4.0 TEST PROCEDURE

The test specimen blanks were taken from the billet and solution treated prior to machining. All specimens were standard Boeing test specimens and are presented in Figure 5. Since the test specimens were finish machined prior to the aging treatment, they required repolishing after the aging cycle to remove the slightly discolored surface. The fatigue specimens were polished in the longitudinal direction to remove any scratches in the transverse direction which might affect the fatigue life. The Charpy and the notch bend fracture toughness specimens were all pre-cracked after final aging to insure a fresh crack with no blunting of the crack tip.

The fatigue specimens and the fatigue test fixture were Boeing designed. These specimens can be tested in compression fatigue as well as tension fatigue because of the special rigid-grip fixture. These test specimens are not threaded and are firmly held by collet chucks at each end to assure alignment. Smooth specimens ($K_t = 1$) were used for base line fatigue data and notched specimens ($K_t = 3.3$) were used to determine the effect of a sharp notch on the fatigue life.

5.0 TEST RESULTS

5.1 Tensile Tests

The tensile results are presented in Table I. The average ultimate tensile strength for 6 specimens was 225 ksi with very good reduction in area and good elongation. Six additional tensile specimens were cryogenically cooled to -100°F after solution treating and aged at (4) different aging temperatures. The tensile properties of these specimens aged at 925, 950, and 975°F showed almost identical values and it appears that PH13-8Mo is not sensitive to minor aging temperature variations in this temperature range. However, there was a slight decrease in strength when the specimen was aged at 1000°F which indicates that overaging is starting to occur. The heat treat study in Figures 3 and 4 shows the effect of aging temperature on the microstructure. A plot of the tensile ultimate strength as a function of aging temperature is presented in Figure 6.

5.2 Fracture Toughness Tests

5.2.1 The notch bend specimens were used to establish the fracture toughness (K_{Ic}) values. Other specimens such as the standard Charpy impact and precracked Charpy impact were used for supplemental information.

Three notch bend specimens that were aged at the standard 950°F temperature gave an average fracture toughness value of 96.4 ksi$\sqrt{in}$. The three test values were very close together with only a difference of 2.6 ksi$\sqrt{in}$ between the two extremes.. The test data are presented in Table II. Also included in Table II are the test data for Charpy size fracture toughness specimens which were aged at 925°F, 950°F, 975°F, and 1000°F. The effect of aging temperature on the fracture toughness is plotted in Figure 7. It can be seen that fracture toughness is quite sensitive to aging temperatures and a variation in the aging temperature from 925°F to 1000°F increases the toughness considerably.

5.2.2 The Charpy test results from both the standard and precracked specimens are presented in Table III. The results of the 950°F aged standard Charpy tests indicates considerable scatter in the data. This scatter is probably due to the slight variations in the notch root radius which affects the initiation energy during impact. The precracked data for 950°F aged specimens shows better reproducibility in testing.

The effect of cooling to -100°F after solution treating on Charpy properties was investigated and the data is presented in Table III. It appears on the basis of limited tests that cryogenic cooling improves the standard Charpy values but does not improve the precracked Charpy values as shown in Figure 8. In Figure 9, both the standard and precracked Charpy impact values are plotted as a function of aging temperature to show the effect of aging temperature on impact properties.

5.2.3 The Charpy size specimens were used in the 10 hour and 100 hour exposure test at 800°F, 850°F, and 900°F. The specimens were not stressed during exposure. After exposure, these specimens were precracked and impact tested. The test results are presented in Table IV and the effect of exposure temperature on the impact toughness is plotted in Figure 10. The loss of toughness at 800°F to 900°F is a characteristic of the 12% chromium alloys and the PH13-8Mo is no exception. For this reason, this steel should not be used in the temperature range of 800° to 900°F.

5.3 Stress Corrosion

The stress corrosion tests were conducted in two different types of test fixtures. When the program was first initiated, only the immersion-type 4 point bending fixture was available. Near the end of this program, a new type of fixture which stresses the specimen as a cantilever beam and drips fresh 3-1/2% NaCl solution into the crack was made available for our tests. Test data from both test fixtures are presented in Table V and the stress corrosion is plotted as a function of time in Figure 11.

Most of the 4 point bend specimens were only tested for 6 hours under load since the test equipment was shared with other test programs. One specimen was allowed to run for 66 hours by scheduling the test over a weekend. Most of the 4 point bend specimens, which did not fail in 6 hours of sustained loading, experienced failure on reloading at a lesser stress level. The reasons for this behavior are not readily apparent. Close examination of the fracture surfaces did not disclose any corrosion or stress corrosion evidence.

The cantilever beam tests were allowed to continue for an extended time. One specimen was tested for 1270 hours at an initial stress intensity of 66.9 ksi$\sqrt{\text{in}}$ before the test was discontinued. The specimen did not fail. Another specimen at an initial stress intensity of 68.5 ksi$\sqrt{\text{in}}$ went 800 hours without failure. The test results indicate that this material is quite resistant to stress corrosion failure.

5.4 Fatigue

The fatigue test data for the smooth and notched $K_t = 3.3$) specimens are presented in Table VI and the S-N curves are presented in Figure 12 . The tests were conducted in tension-tension with a stress ratio of R =+.06 and at a rate of 1800 cycles per minute. The tests were conducted to establish the fatigue life at 2.5 million cycles. Tests were stopped at 2.5 million cycles when no failure occurred.

The fatigue life for PH13-8Mo is comparable to 4330 and other high strength steels in the same strength range. This level of fatigue life is acceptable for most heavy section structural applications.

6.0 CONCLUSIONS

1. PH13-8Mo has good strength and toughness at the 225 ksi strength level.

2. The resistance to stress corrosion crack propagation is excellent.

3. The resistance to general atmospheric corrosion is good.

4. The fatigue limit for smooth specimens is comparable to 4330 steel.

5. The combination of good mechanical properties and corrosion resistance makes this alloy very attractive for structural applications.

TABLE I [3]

Tensile Properties

Spec. No.	Heat Treat		TUS	TYS	%El	%RA
8-21	[1]		224.2	207.3	13	56
8-22			225.8	205.3	12	56
8-23			226.3	207.4	13	58
8-24			226.1	207.8	15	61
8-25			225.0	204.5	15	58
8-26	[1]		225.0	207.7	15	61
		Avg.	225.4	206.6	13.5	58.3
13-1	[2] +925F		226.8	206.5	15	61
13-2	[2] +950F		226.5	211.6	16	60
13-3	[2] +950F		226.9	206.9	17	61
13-4	[2] +975F		226.3	206.5	15	62
13-5	[2] +975F		224.2	204.9	15	61
13-6	[2] +1000F		219.7	209.0	14	61
		Avg.	225.1	207.5	15.3	61

[1] Soln. 1 hr @ 1700°F, oil cool to 60°F, age 3 hrs @ 950°F

[2] Soln. 1 hr @ 1700°F, oil cool to 60°F, 8 hrs @ -100°F

[3] **All specimens have longitudinal grain direction parallel to the long axis of the specimen.**

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TABLE II 7

Fracture Toughness Properties

Spec. No.	Heat Treat 1	B in	W-a (in)	P_{max} (KIPS)	K_{Ic} ksi $\sqrt{in}$
8-47	3	.48	1.18	18.1	98.1
8-48	3	.48	1.17	24.3	95.6
8-49	3	.48	1.18	20.8	97.6
					Avg. 97.1
13-25	2	.48	1.19	14.00	64.4
13-26	3	.48	1.19	19.05	87.6
13-27	3	.48	1.19	17.30	79.6
13-28	4	.48	1.18	26.85	103.5
13-29	4	.48	1.19	26.35	107.2
13-30	5	.48	-	30.00 6	6

1. All specimens solution treated 1 hour @ 1700F
2. Aged 3 hours @ 900F
3. Aged 3 hours @ 950F
4. Aged 3 hours @ 975F
5. Aged 3 hours @ 1000F
6. Did not fail
7. **All specimens have longitudinal grain direction parallel to the long axis of the specimen.**

TABLE III - STANDARD AND PRECRACKED CHARPY PROPERTIES 7

Spec. No.	Heat Treat 1	Uncracked Area (in^2)	Impact Energy ft-lb	Impact Energy in-lb	W/A ($In\text{-}lb/in^2$)
8-31	4	.124	9.0	-	-
8-32	4	.124	26.0	-	-
8-33	4	.124	15.0	-	-
8-34	4	.124	11.8	-	-
8-35	4	.124	12.8	-	-
13-7	2 + 3	.124	18.9	-	-
13-9	2 + 4	.124	20.8	-	-
13-13	2 + 5	.124	>24.0	N.F.	-
13-17	2 + 6	.124	>24.0	N.F.	-
8-42	2 + 5	.124	8.5	-	-
8-44	2 + 6	.124	34.3	-	-
8-27	4	.1143	-	63.8	558.2
8-28	5	.1064	-	55.6	522.6
8-29	6	.1156	-	42.4	366.8
				Avg.	482.5
13-8	2 + 3	.114		27.7	243
13-10	2 + 3	.116		34.8	297
13-11	2 + 4	.116		34.8	297
13-12	2 + 4	.118		44.4	373
13-14	2 + 5	.119		67.9	571
13-15	2 + 5	.116		81.4	702
13-16	2 + 5	.112		89.8	802
13-18	2 + 6	.118		146.5	1242

1. All specimens solutioned 1 hr. @ 1700°F
2. 8 hrs. @ -100°F after solution
3. Aged 3 hrs. @ 925°F
4. Aged 3 hrs. @ 950°F
5. Aged 3 hrs. @ 975°F
6. Aged 3 hrs. @ 1000°F
7. All specimens have longitudinal grain direction parallel to the long axis of the specimen

TABLE IV - IMPACT PROPERTIES ON THERMALLY EXPOSED SPECIMENS 1

Spec. No.	Exposure Temperature (°F)	Exposure Time (hours)	Uncracked Area (in.^{2})	W/A in-lb/in.^{2}
8-36	800	10	.1103	174.5
8-39	800	100	.1140	136.0
8-37	850	10	.1137	214.6
8-40	850	100	.1123	154.9
8-38	900	10	.1180	393.6
8-41	900	100	.1024	184.6

1 All specimens have longitudinal grain direction parallel to the long axis of the specimen

TABLE V - STRESS CORROSION PROPERTIES 7

Spec. No.	Heat Treat 1	(in)	W-a (in)	(KIPS)	Time to Failure	K_{Ii} (ksi$\sqrt{in}$)	Remarks
8-50	2	.48	1.17	15.14	NF in 6 Hrs.	72.4	3
8-51	2	.48	1.15	16.95	NF in 6 Hrs.	84.1	3
8-51	2	.48	1.15	16.95	0	84.1	3 4
8-52	2	.48	1.16	19.10	0	93.1	3
8-53	2	.48	1.15	18.15	NF in 6 Hrs.	90.0	3
8-54	2	.45	1.09	16.10	NF in 6 Hrs.	94.7	3
8-54	2	.45	1.09	17.68	0	104.0	3 4
13-19	5 2	.48	1.19	2.905	0	75.5	6
13-20	5 2	.48	1.18	2.905	0	76.7	6
13-21	5 2	.48	1.18	2.750	0	72.5	6
13-22	5 2	.48	1.19	2.670	800 Hrs.	68.5	6
13-23	5 2	.48	1.19	2.460	1270 Hrs.	66.9	6

1 All specimens solution treated 1 hr. @ 1700°F

2 Aged 3 hrs. @ 950°F

3 Tested in 4-point loading in 3-1/2% NaCl solution

4 Failed on reloading after no failure for 6 hours

5 Sub-zero cooled 8 hrs. @ -100°F

6 Tested in cantilever beam

7 **All specimens have longitudinal grain direction parallel to the long axis of the specimen.**

TABLE VI ▷1

FATIGUE PROPERTIES

Spec. No.	Notch Factor Kt	Max. Stress ksi	Stress Ratio R	Cycles to Failure
8-1	1.0	90.0	0.06	2,600,000 NF
8-2		135.0		3,494,000 NF
8-3		180.0		50,000
8-4		180.0		91,000
8-5		180.0		59,000
8-6		135.0		2,500,000 NF
8-7		135.0		310,000
8-8		202.5		20,000
8-9		202.5		15,000
9-10	1.0	202.5	0.06	23,000
8-11	3.3	90.0	0.06	32,000
8-12		49.5		845,000
8-13		90.0		21,000
8-14		49.5		823,000
8-15		90.0		18,000
8-16		49.5		2,872,000 NF
8-17		135.0		4,000
8-18		135.0		5,000
8-19		135.0		4,000
8-20	3.3	49.5	0.06	2,555,000 NF

▷1 All specimens have longitudinal grain direction parallel to the long axis of the specimen

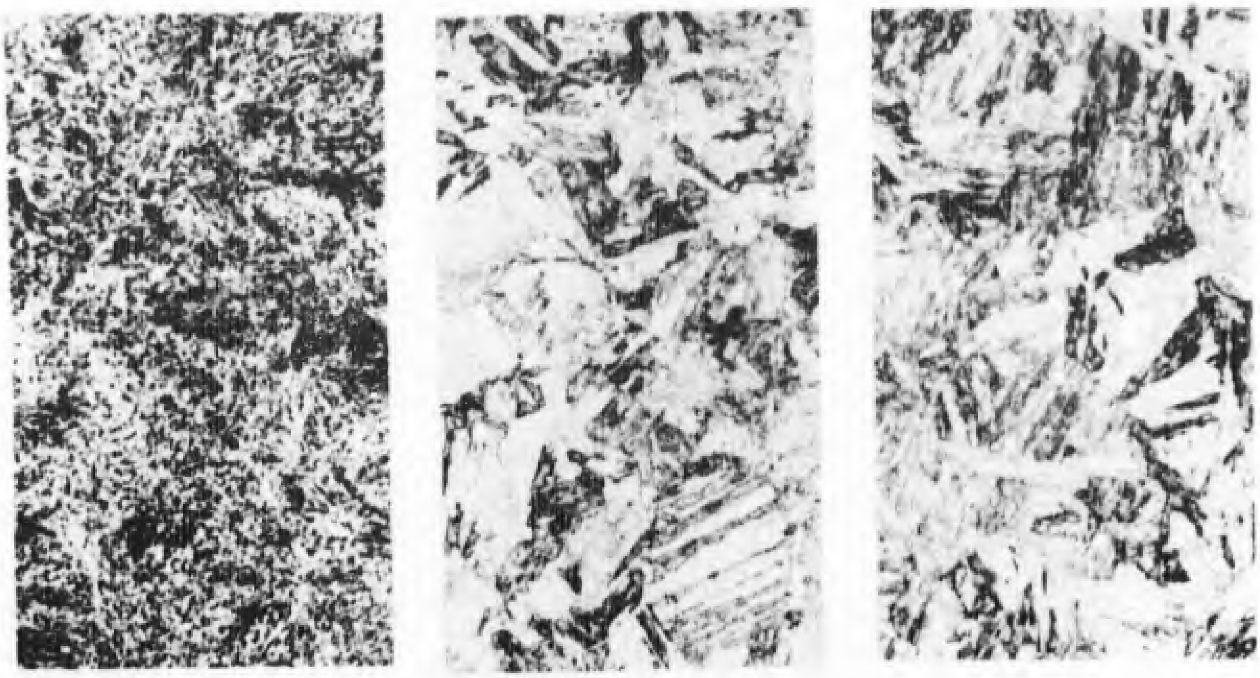
ETCH: 4 HCl
1 HNO_3
4 H_2O

TEMP: 160°F

MAGNIFICATION
.85X

FIGURE 1

MACRO SECTION OF BILLET



SOLUTIONED AT 1600°F
AGED 3 HRS AT 950°F
MAGNIFICATION 500X
FRY'S ETCH

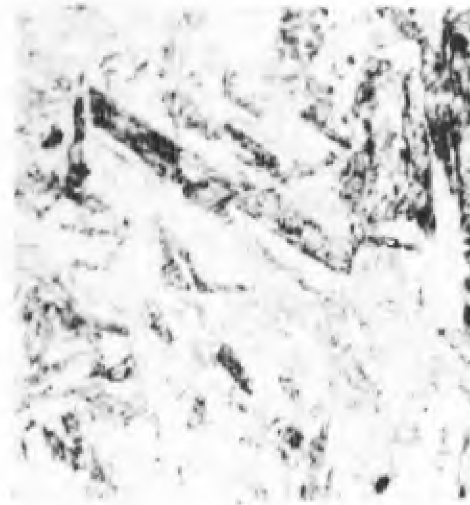
SOLUTIONED AT 1700°F
AGED 3 HRS AT 950°F
MAGNIFICATION 500X
FRY'S ETCH

SOLUTIONED AT 1800°F
AGED 3 HRS AT 950°F
MAGNIFICATION 500X
FRY'S ETCH

FIGURE 2

EFFECT OF SOLUTION TREAT TEMPERATURE
ON THE MICROSTRUCTURE

3 HRS @ 700°F RC 37



3 HRS @ 800°F RC 42

3 HRS @ 850°F RC 46

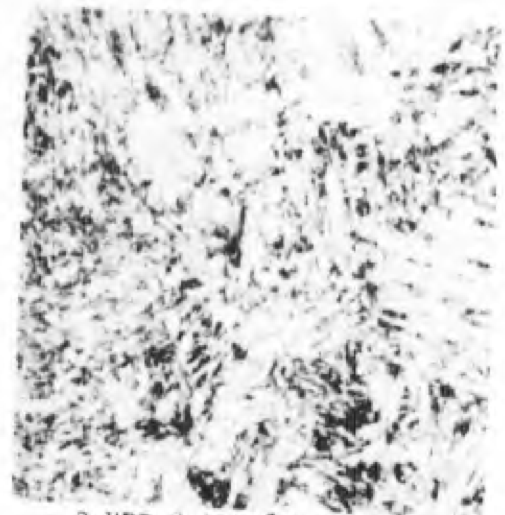
3 HRS @ 900°F RC 46.5

3 HRS @ 950°F RC 46

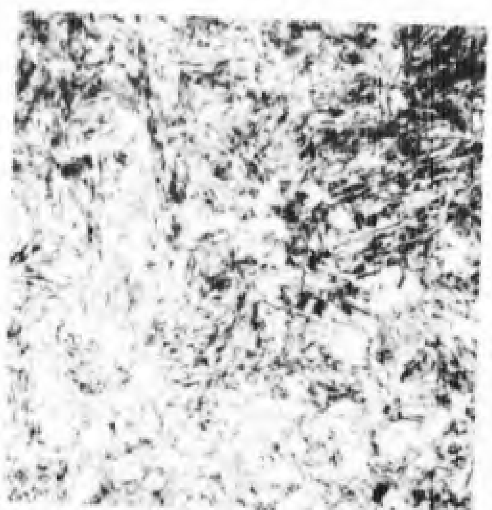
3 HRS @ 1000°F RC 46

FIGURE 3
AGING STUDY
SOLUTIONED AT 1700°F; AGED AS INDICATED: MAG 500X;FRY'S ETCH

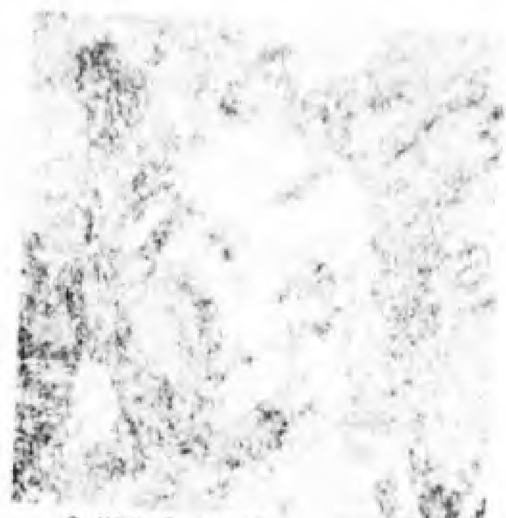
3 HRS @ 1050°F RC 43



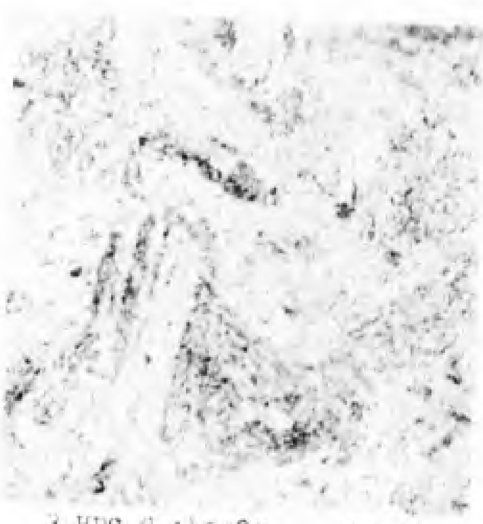
3 HRS @ 1100°F RC 43



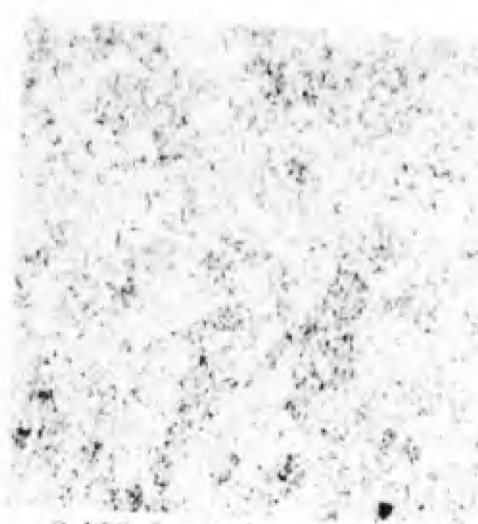
3 HRS @ 1200°F RC 33



3 HRS @ 1300°F RC 31



3 HRS @ 1400°F RC 32



3 HRS @ 1500°F RC 33.5

FIGURE 4

AGING STUDY

SOLUTIONED AT 1700°F, AGED AS INDICATED: MAG 500X; FRY'S ETCH

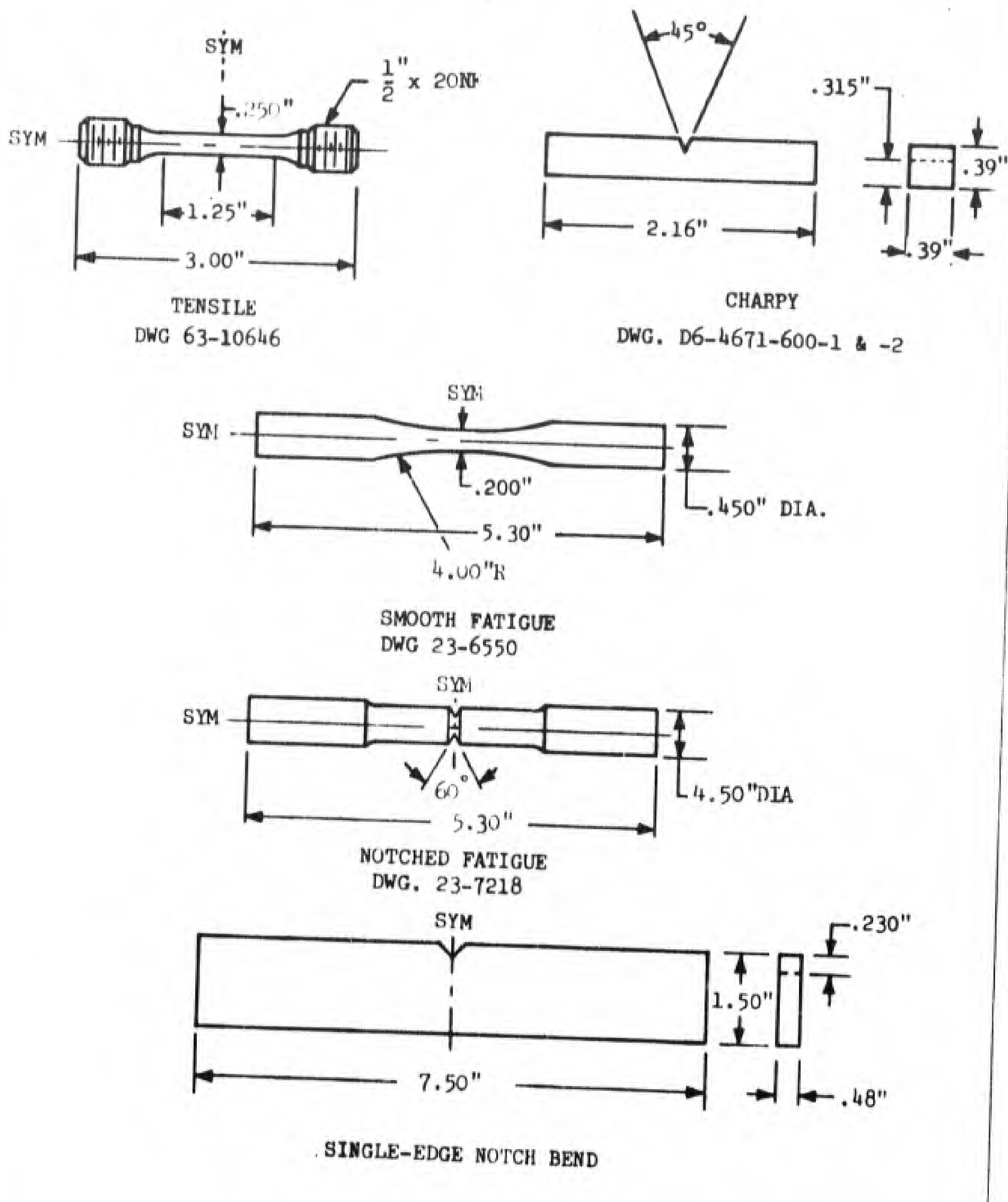


FIGURE 5

TEST SPECIMENS

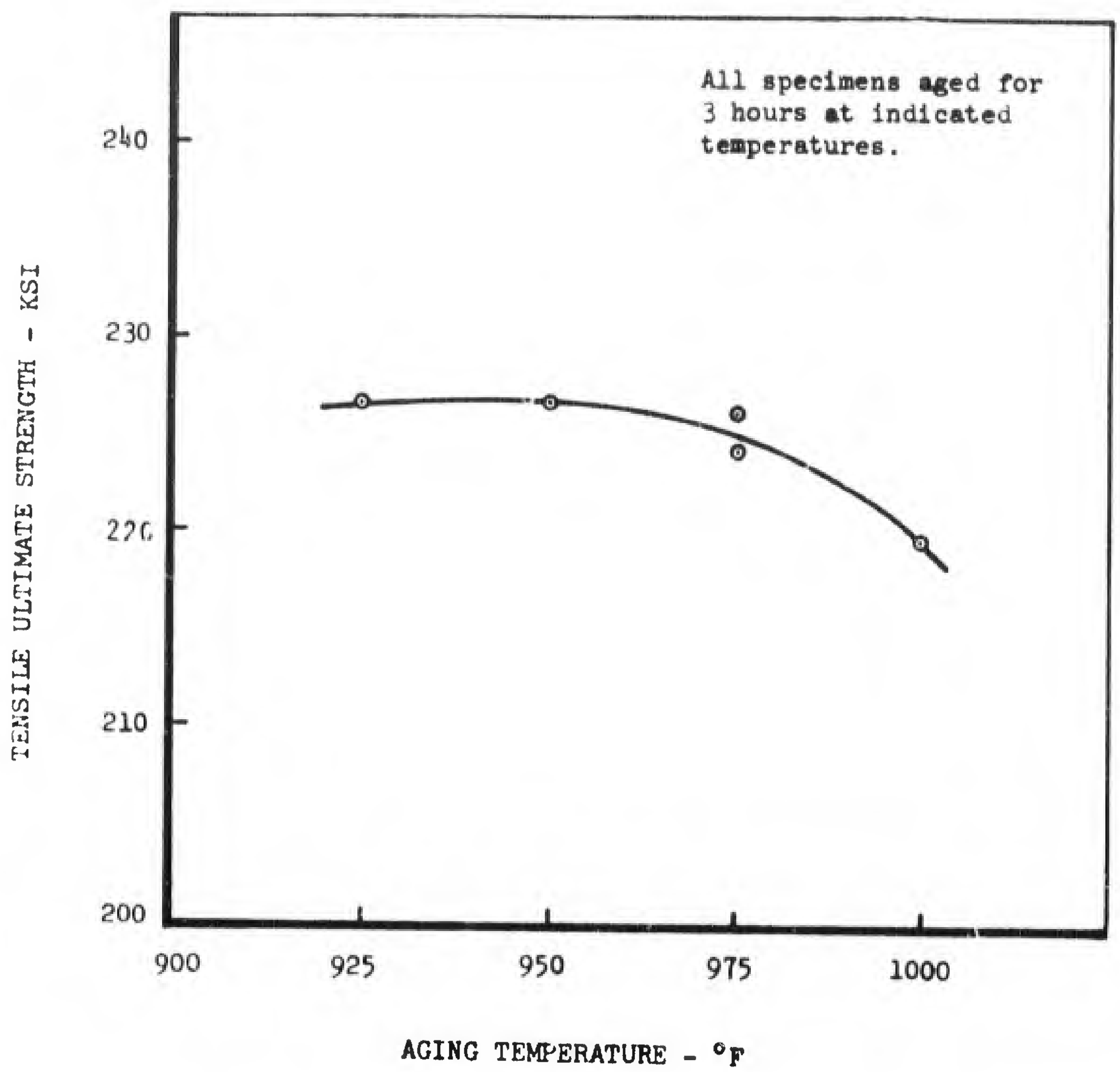


FIGURE 6

EFFECT OF AGING TEMPERATURE
ON TENSILE ULTIMATE STRENGTH

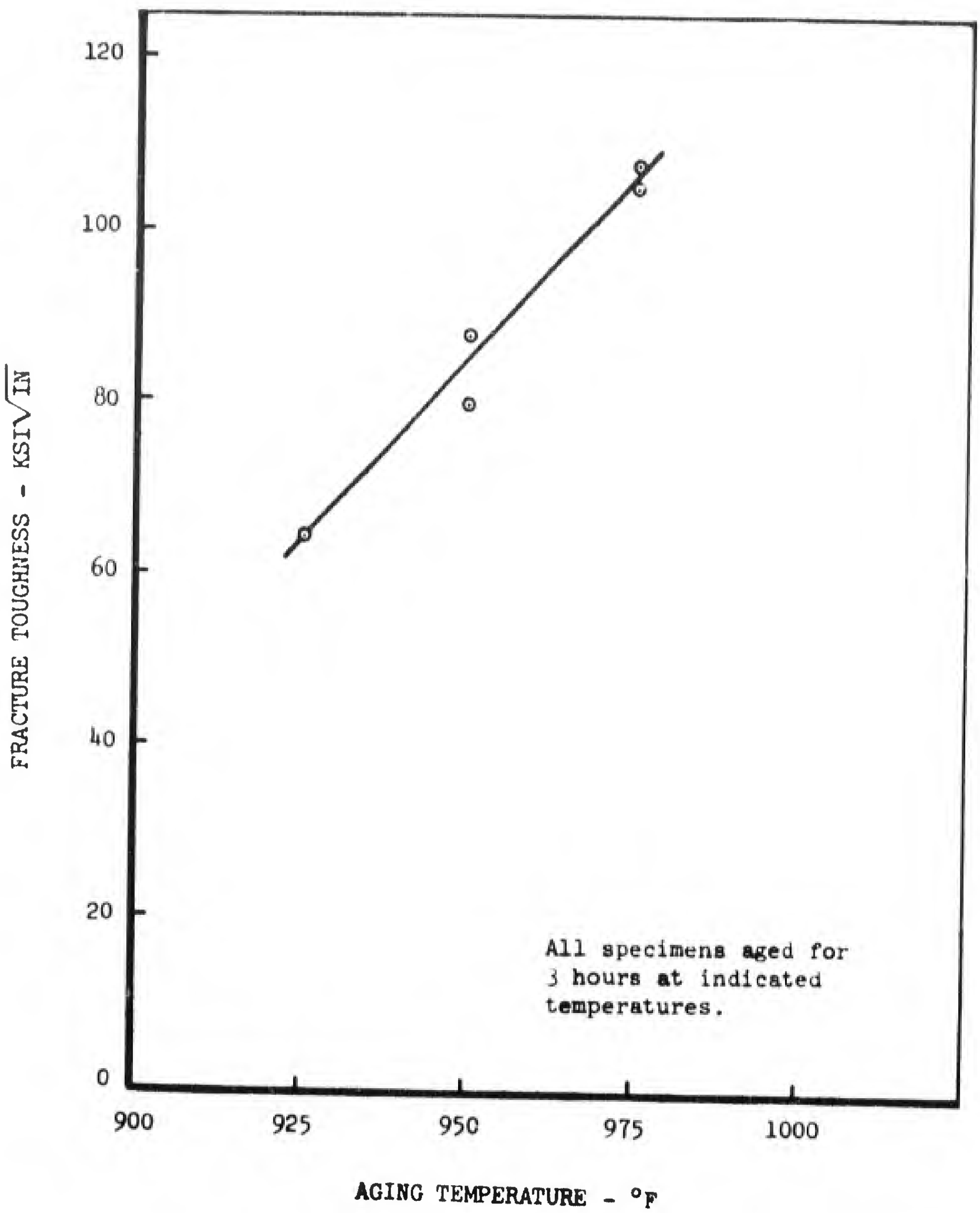


FIGURE 7

EFFECT OF AGING TEMPERATURE
ON FRACTURE TOUGHNESS

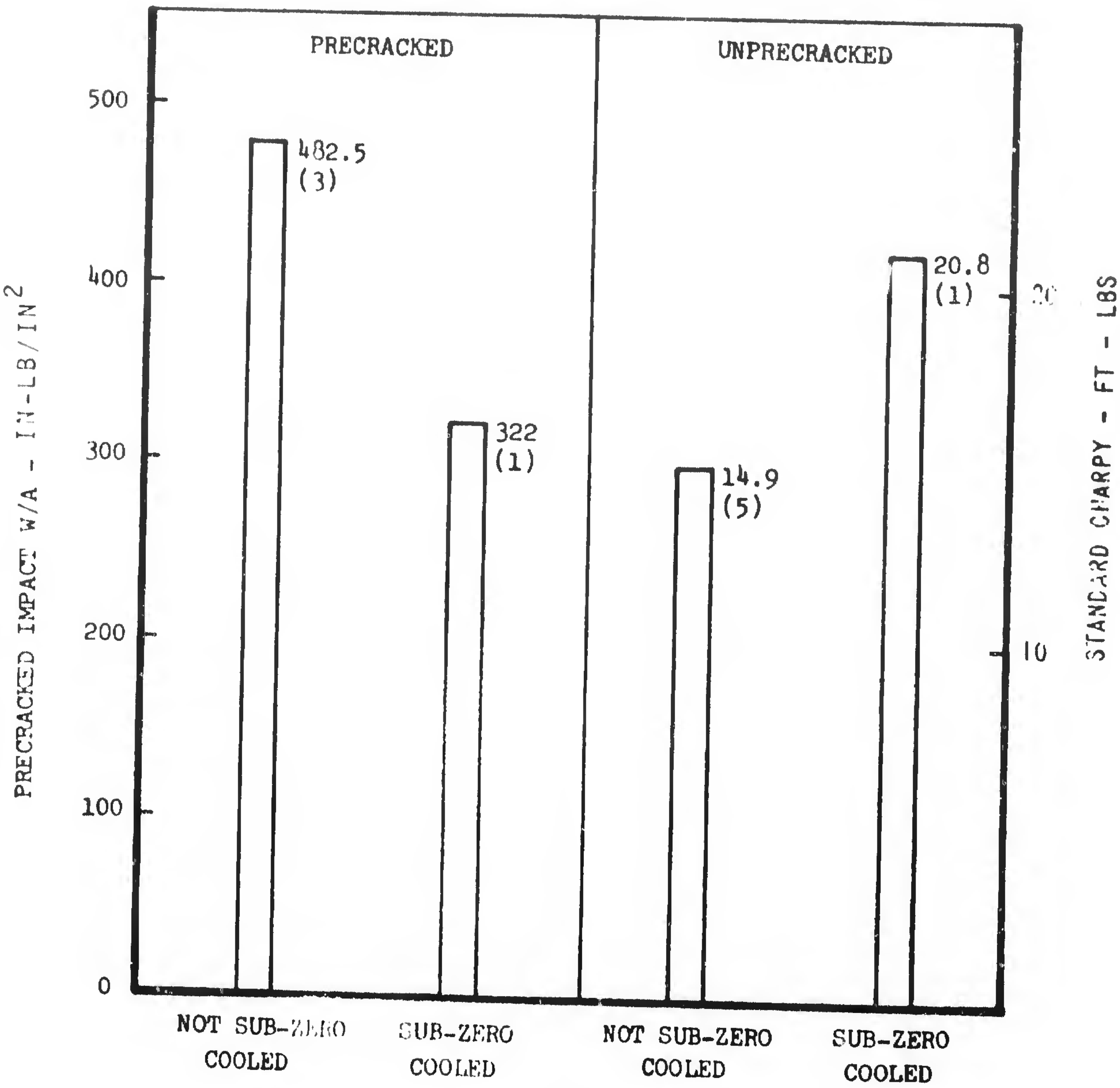


FIGURE IN ( ) DENOTES NUMBER OF SPECIMENS

FIGURE 8

COMPARISON OF IMPACT PROPERTIES BETWEEN
SUB-ZERO COOLED & NON SUB-ZERO COOLED SPECIMENS

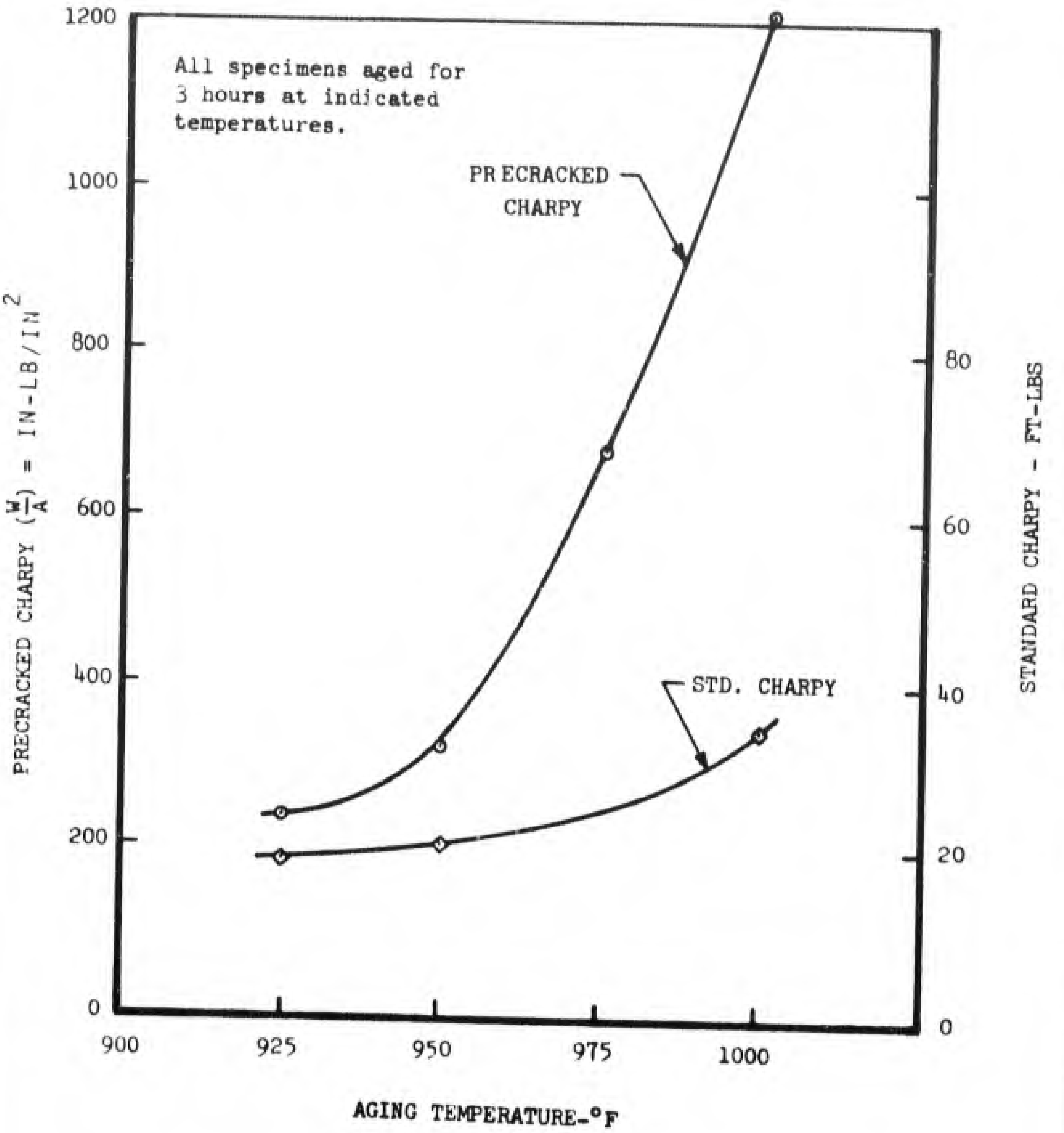


FIGURE 9

EFFECT OF AGING TEMPERATURES ON
CHARPY IMPACT PROPERTIES

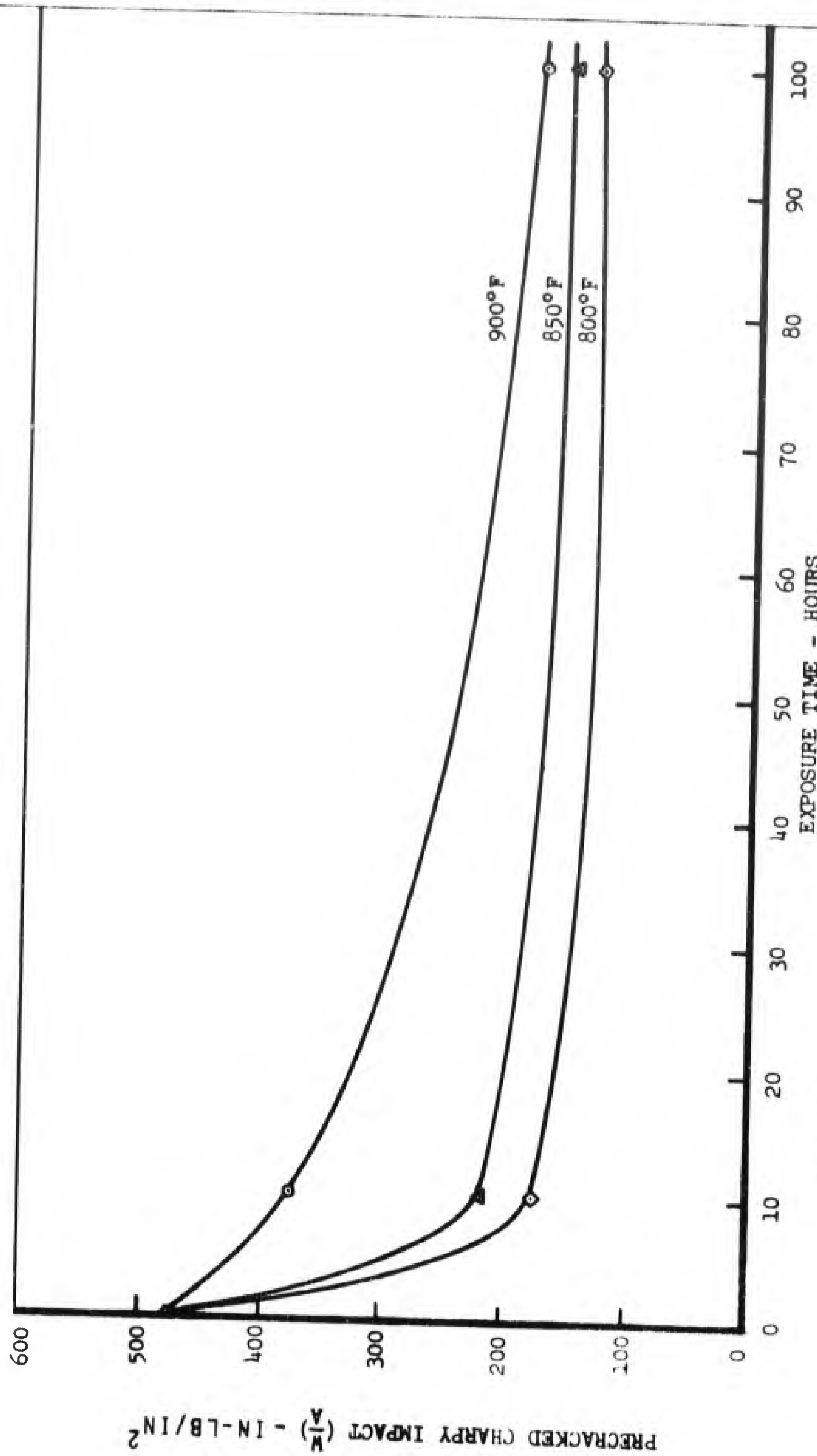


FIGURE 10 EFFECT OF EXPOSURE TEMPERATURE ON IMPACT TOUGHNESS

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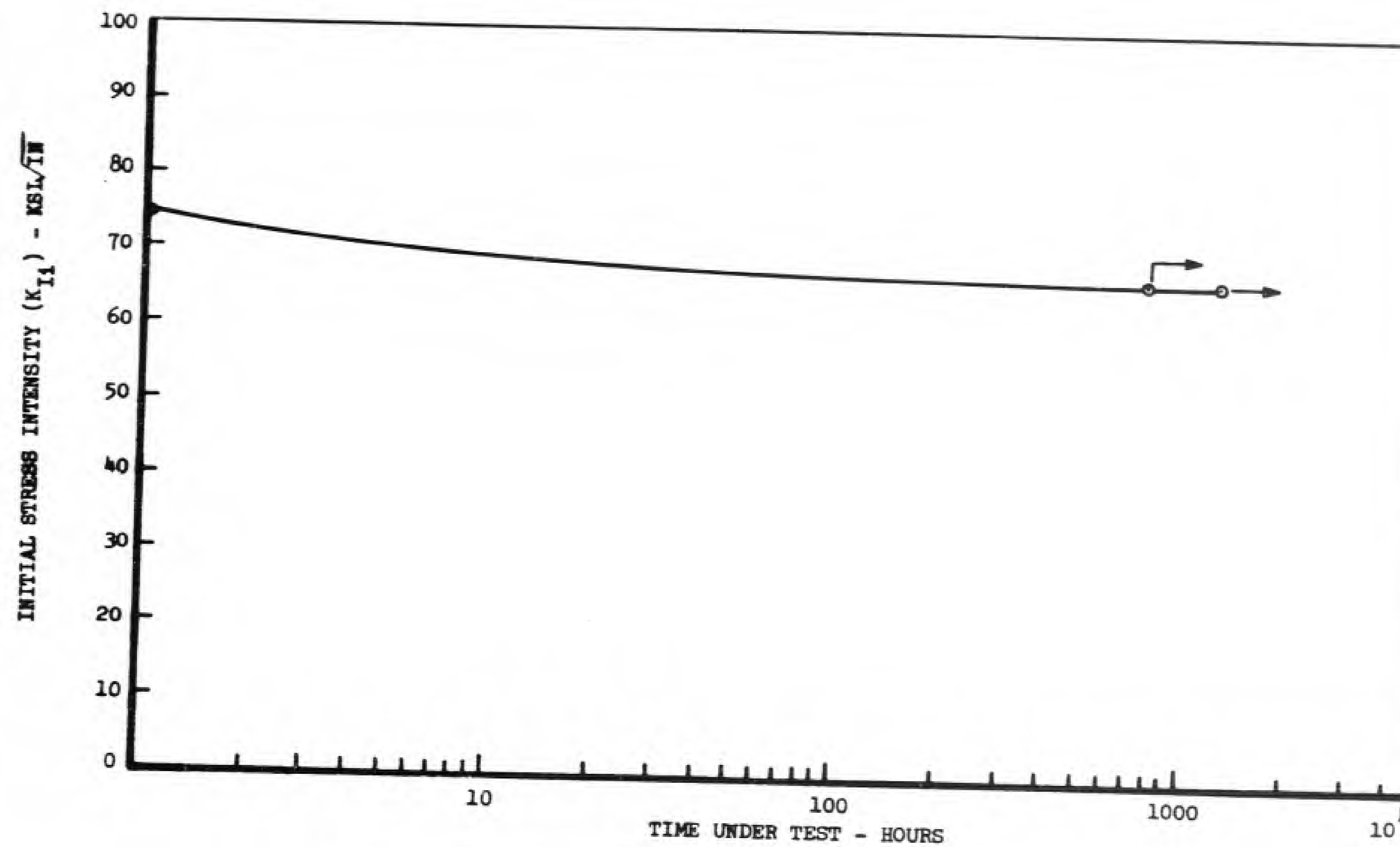

FIGURE 11 STRESS CORROSION AS A FUNCTION OF TIME

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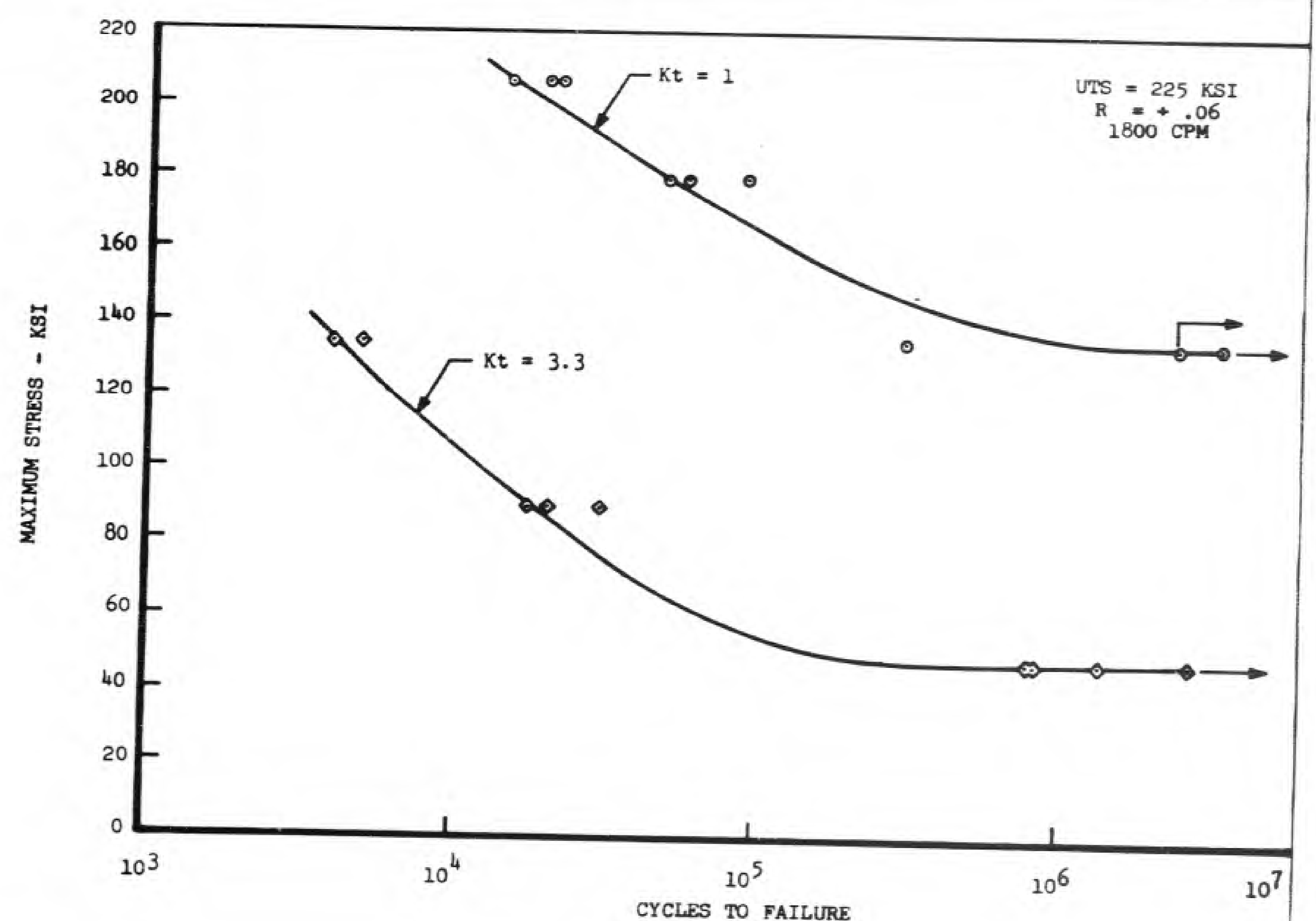

FIGURE 12 AXIAL FATIGUE DATA